MEASUREMENTS OF THE VORTEX EXCITED STRUMMING VIBRATIONS OF MARINE CABLES

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ABSTRACT

Field experiments were conducted during the summer of 1981 to study the strumming vibrations of marine cables. One of the objectives of the experiments was to validate and, if necessary, to provide a data base for modifying the computer code NATFREQ. This code was developed at the California Institute of Technology for the Naval Civil Engineering Laboratory (NCEL) to calculate the natural frequencies and mode shapes of taut cables with large numbers of attached discrete masses. Time histories of the measured hydrodynamic drag coefficients, current speeds, and cable strumming responses are presented here for selected test runs with a bare cable and for a cable with attached masses. Also, a comparison is made between NATFREQ- predicted and measured natural frequencies and mode shapes for the test cable.

INTRODUCTION

The vortex-excited oscillations of marine cables, commonly termed strumming, result in early fatigue, larger hydrodynamic forces and amplified flow noise, and sometimes lead to structural damage and eventually to costly failures. Flow-excited oscillations very often are a critical factor in the design of underwater cable arrays, mooring systems, drilling risers, and offshore platforms, since the components of these complex structures usually have bluff cylindrical shapes which are conducive to vortex shedding when flowing water is incident upon them. An understanding of the basic nature of vortex-excited oscillations is an important consideration in the reliable and economical design and operation of offshore structures and cable systems. The resonant strumming response of bare cables is discussed in detail in a recent NCEL/NRL report (1). The suppression of strumming vibrations is dealt with in a separate NCEL-sponsored report (2).

As part of the overall NCEL cable dynamics research program, a series of laboratory and field experiments have been conducted to investigate the effects of attached masses and sensor housings (discrete or lumped masses) on the overall cable system response. Towing channel experiments were conducted with a "strumming rig" developed for the NCEL cable dynamics program and the test findings recently were reported (3). A test program was conducted during the summer of 1981 to investigate further the strumming vibrations of marine cables in a controlled field environment. The experiments were funded by NCEL, the USGS and industry sponsors, planned by NRL and MIT, and conducted at the field site by MIT. A primary objective of the test program was to acquire data to validate and, if necessary, to provide a basis for modifying the NCEL-sponsored computer code NATFREQ (4). This code was developed in order to calculate the natural frequencies and mode shapes of taut marine cables with large numbers of attached masses.

The purpose of this paper is to describe the field test program and to present some initial results from it. Also, calculations using the NATFREQ code have been made at NRL for all of the field test runs and a comparison is made with selected test data that have been analyzed in sufficient detail. Time histories of the measured hydrodynamic drag coefficients, current speeds, and cable strumming responses are presented and discussed. Predictions are made of the hydrodynamic drag on a bare cable and these predictions are compared with the field test data for selected conditions when the cable was observed to be resonantly strumming.

THE TEST SITE AND INSTRUMENTATION

The Test Site

The site chosen for the experiment was a sandbar located at the mouth of Holbrook Cove near Castine, Maine. This was the same site used for previous experiments during the mid-1970's by Vandiver and Mazel (5,6). At low tide the sandbar was exposed allowing easy access to the test equipment, while at high tide it was covered by about ten feet of water. The test section was oriented normal to the direction of the current which varied from 0 to 2.4 ft/s over the tidal cycle with only small spatial variation over the test section length at any given moment.

The data acquisition station for the experiment was the *R/V Edgerton* which was chartered from the MIT Sea Grant Program. The *Edgerton* was moored for the duration of the experiment approximately 300 feet from the sandbar and connected to the instruments on the sandbar by umbilicals.

Prior to the data acquisition phase of the experiment, several days were needed to prepare the site. A foundation for the experiment was needed to anchor the supports which were to hold the ends of the test cylinders. To accomplish this, six 4.5 inch diameter steel pipes were water jetted into the sandbar utilizing the fire pump aboard the *Edgerton*. These six pipes were made of two five foot sections joined by couplings so that the overall length of each was ten feet. In addition, one two-inch diameter by six foot long steel pipe was jetted into the sandbar to be used as a current meter mount. Finally, a section of angle iron was clamped to the pipe used to support the drag measuring mechanism and attached to another support pipe to prevent any rotation of the drag mechanism mount. Figure 1 shows a schematic diagram of the set-up of the experiment.

Test Instrumentation

Drag measurement system. The drag measurement system was located at the west end of the cable system as shown in Figure 1. The device was welded onto a support pipe 2.5 feet above the mud line. The mean drag force at the termination of the cable was used to generate a moment about a freely rotating vertical shaft located a few inches beyond the termination point. The bearings supporting the shaft carried the entire tension load without preventing rotation. The moment was balanced by a load cell which restrained a lever arm connected to the shaft (see Figure 2). From the known level-arm lengths and the load cell measurements the mean drag force on one half of the cable could be determined. The load cell signal was carried by wires in the cable and umbilical to the *Edgerton* where it was conditioned and recorded.

Current measurement system. The current was measured by a Neil Brown Instrument Systems DRCM-2 Acoustic Current Meter located 12.5 ft from the west end of the test cable and 2 ft upstream. It was set so that it determined both normal and tangential components of the current at the level of the test cable. Signals from the current meter traveled through umbilicals to the *Edgerton* where they were monitored and recorded. In addition, a current meter traverse was made using an Endeco current meter to determine any spatial variations in current along the test section. The current was found to be spatially uniform to within 3.0 percent from end to end for all but the lowest current speeds ($V < 0.5$ ft/s).

Tension measurement system. The tension measuring and adjusting system was located at the east end of the experimental test set up (see Figure 1). Extensions were made to the two inner water jetted posts at this end. As shown in the diagram, a five foot extension was made to the center post and a three foot extension was made to the innermost post. This three foot extension was different from the rest in that its attachment to the jetted pipe at the mudline was a pin connection as compared to the standard pipe couplings used on the other extensions. Onto this pivoting post, a hydraulic cylinder was mounted 2.5 feet above the mudline. The test cable in the experiments was connected at one end to this hydraulic cylinder and at the other end to the drag measuring device. To the back of the hydraulic cylinder one end of a Sensotec Model RM In-Line load cell was connected. The other end of the cell was attached via a cable to the center post. The output from the tension load cell was transmitted through the umbilicals to the *Edgerton* where it was monitored. Hydraulic hose ran from a pump on the *Edgerton* to the hydraulic cylinder so that the tension could be changed as desired. Additional details concerning the test instrumentation are given by McGlothlin (7).

Data Acquisition Systems

During the experiment, data taken from the instruments on the sandbar were recorded in two ways. First, analog signals from the fourteen accelerometers in the cable as well as current and drag were digitized, at 30.0 Hz per channel, onto floppy disks using a Digital Equipment MINC-23 Computer. Second, analog signals from the drag cell, current meter, and six accelerometers were recorded by a Hewlett-Packard 3968A Recorder onto eight-track tape. The disks were limited to record lengths of eight and one half minutes and were used to take data several times during each two and one half hour data acquisition period. A Hewlett-Packard 3582A Spectrum Analyzer was set up to monitor the real time outputs of the accelerometers. The eight-track tape was used to provide a continuous record of the complete two and one half hour data cycle.

THE TEST CABLE SYSTEM

The Cable

A 75 foot long composite cable was developed specifically for the experiments that were conducted in the summer of 1981. Figure 3 shows a cross-section of the test cable. The outer sheath for this cable was a 75 foot long piece of clear flexible PVC tubing, which was 1.25 in. O.D. by 1.0 in. I.D. Three 0.125 in. stainless steel cables ran through the tubing and served as the tension carrying members. A cylindrical piece of 0.5 in. O.D. neoprene rubber was used to keep the stainless steel cables spaced 120 degrees apart. The neoprene rubber spacer was continuous along the length except at seven positions where biaxial pairs of accelerometers were placed. Starting at the east end, these positions were at L/8, L/6, L/4, 2L/5, L/2, 5L/8, and 3L/4. These accelerometers were used to measure the response of the cable as it was excited by the vortex shedding. The accelerometers were Sundstrand Mini-Pal Model 2180 Servo Accelerometers which were sensitive to the direction of gravity. The biaxial pairing of these accelerometers made it possible to determine their orientation and to extract real vertical and horizontal accelerations of the cable at the seven locations.

Three bundles of ten wires each ran along the sides of the neoprene spacer to provide power and signal connections to the accelerometers and also to provide power and signal connections to the drag measuring system. Finally, an Emerson and Cuming flexible epoxy was used to fill the voids in the cable and make it watertight. The weight per unit length of this composite cable was 0.77 lb/ft in air.

The Attached Masses

In some experiments, lumped masses were fastened to the bare cable to simulate the effects of sensor housings and other attached bodies. The lumped masses were made of cylindrical PVC stock and each was 12.0 in. long and of 3.5 in. diameter. A 1.25 in. hole was drilled through the center of each lumped mass so that the cable could pass through. In addition, four 0.625 in. holes were drilled symmetrically around this 1.25 in. center hole so that copper tubes filled with lead could be inserted to change the mass of the lumps. In the field, it was difficult to force the cable through the holes drilled in the PVC so the masses were split in half along the length of their axes. The masses were then placed on the cable in halves and held together by hose clamps. Different tests were run by varying the number and location of lumped masses and by changing the mass of the attachments.

MEASUREMENTS OF CABLE STRUMMING

Bare Cable

Several test runs were conducted with the bare cable during the experiments to provide a basis for comparison to the cable with attached masses. A 300 second time history for one bare cable test run is shown in Figure 4. The cable was resonantly strumming at 1.9 Hz in the third mode normal to the current and non-resonantly vibrating in the fifth mode in line with the flow at 3.8 Hz. The vertical and horizontal RMS displacement amplitudes were derived from the time records of the accelerometer pair at a location L/6 along the cable. For the third mode this location corresponds to an antinode of the cable vibration. The fifth mode amplitudes at this location are one-half the antinode maximum. The vertical displacement amplitude is approximately ± 0.6 to 0.7 diameters (RMS) over the length of the record. The tension in this test was 360 pounds. The damping ratio measured in air for the third mode was 0.15 percent. The reduced damping (1) for this cable was $\zeta_s/\mu = 2\pi St^2 k_s = 0.06$.

The average drag force coefficient on the cable is approximately $C \cong 3.2$; this is considerably greater than the drag coefficient $C_{DO} = 1.2$ that would be expected if the cable were restrained from oscillating under these flow conditions. The drag coefficient on the strumming cable was predicted with the equation

$$C_{D,\mathrm{AVG}} = C_{DO}\ [1 + 1.043\ (2\overline{Y}_{RMS}/D)^{0.65}],$$

which is derived from the original equation proposed by Skop, Griffin and Ramberg (8,9). Here C_{DO} is the stationary cable drag coefficient. This equation takes into account the modal distribution in displacement amplitude along the cable. $\overline{Y}_{RMS}/D$ is the root-mean-square antinode displacement in diameters. The strumming drag coefficient predicted using this equation is in the range C_D = 2.4 to 2.6 as shown in Figure 4; this is approximately 15 percent below the drag force coefficient measured at the field site. The results of these field test runs clearly verify the large amplification in hydrodynamic drag due to strumming that has been measured previously in laboratory-scale experiments (1,8,9).

Cable with Attached Masses

Ten test runs were conducted at the field site with different combinations of locations, numbers, and masses of the attached cylindrical lumps. Tests were run in air and in water for each of the ten combinations. The in-air tests provided measures of the structural damping from vibration decay tests and of the natural frequencies and mode shapes. An example taken from one of the more complex test runs is shown in Figure 5. Six masses were attached to the cable: two light cylinders (m = 4.4 lb_m or 2 kg) at x = L/8 and L/2; and four heavy cylinders (m = 10.0 lb_m or 4.5 kg) at x = L/3, 5L/8, 3L/4 and 7L/8. The RMS strumming response data shown for a two and one half hour time period in Figure 5 were recorded at x = 3L/4, where both one of the attached masses and an accelerometer pair were located.

Several important results of the experiments can be observed from Figure 5. The vibration level over the time of the test run was approximately 0.3 diameters (RMS), indicating that the attached mass did not act as a node of the cable system vibration pattern. The drag coefficient of the system was C_D = 2.4 to 3.2 which again represented a substantial amplification from the stationary cable value of $C_{DO} \cong 1.2$. The relative contributions have not yet been determined. Several segments of the time history in Figure 5 exhibit nearly constant drag and vertical RMS response levels; this is indicative of resonant lock-on between the cable vibrations and the current-induced vortex shedding. A more detailed assessment of the cable system strumming data is underway to provide further understanding of the strumming phenomenon and additional guidance for marine cable system designers.

NATFREQ PREDICTIONS

The natural frequencies and mode shapes for the field test runs were calculated at NRL with the NCEL-developed computer code NATFREQ (4). This code was developed to calculate the properties of taut cables with large numbers of attached discrete masses. The equations of motion are solved by an iterative technique which allows the accurate calculation of extremely high mode numbers. It is possible with NATFREQ also to calculate the strumming drag on the cable according to the method of Skop, Griffin and Ramberg (8,9), exclusive of the drag due to any of the attached masses.

Computations were made for all of the MIT test runs, both in air and in water. The first twelve natural frequencies and mode shapes were computed, though typically only the first six cable strumming modes were excited by the currents at the test site. An example of the mode shapes is given in Figure 6. For this case the cable was fitted with seven attached 4.4 lb_m lumps. The lumps were equally spaced at intervals of the cable length divided by eight. That is, at distances from one end specified by NL/8, for N = 1 to 7.

A partial tabulation of calculated and measured natural frequencies for the same distribution of attached masses is given in Table 1. The measurements were obtained from vibration decay tests conducted in air. Typical damping ratios were 0.2 to 0.5 percent of the critical damping. Excellent agreement was obtained between the measured and computed frequencies for several of the natural cable modes. These results give a first indication of the applicability of NATFREQ to the calculation of the flow-induced vibrations of full-scale marine cable systems. Additional comparisons between the field measurements and the code predictions are underway.

SUMMARY AND CONCLUDING REMARKS

A test program has been conducted to investigate the effects of attached masses and sensor housings on the strumming response of marine cable systems. The tests were conducted during the summer of 1981 to investigate the strumming response of marine cables in a well-controlled field environment. This paper describes the test set-up, the instrumentation used, and some of the results obtained at the site.

Both an instrumented bare cable and the same cable with varying numbers and types of attached masses were employed in the experiments. The hydrodynamic drag coefficient for the bare cable was measured over extended time periods of up to two and one half hours. The measured average drag force coefficient was as large as $C_D = 3.2$, as compared to $C_{DO} \cong 1.2$ for a non-strumming bare cable under the same flow conditions. Vibrations were excited in the first six strumming modes of the cable at levels up to ± 0.6 to 0.7 diameters (RMS).

Table 1 — Measured and NATFREQ-Predicted
Natural Frequencies (In Air)

Seven 4.4 lb_m Attached Discrete Masses at:

NL/8, for N = 1 to 7.

Natural Frequency, f_n/Hz		
Mode Number	Predicted	Measured
1	0.759	---
2	1.513	1.540
3	2.257	---
4	2.983	3.066
5	3.675	---
6	4.301	---
7	4.787	5.040
8	7.710	---

Cable specifications:

Length, L = 75 ft; Diameter, D = 1.25in.;
Specific Gravity, SG = 1.41;
Tension = 500 lb.

The cable with attached masses also underwent large-amplitude strumming vibrations. In one test described in detail vibration levels of up to ± 0.3 diameters (RMS) were recorded at the location of one of six attached masses over a two and one half hour time period. The measured drag force coefficient on the cable with the six masses was in the range $C_D = 2.4$ to 3.2 over the same time period.

One objective of the field test program was to acquire data to validate and, if necessary, to provide a basis for modifying the NCEL-developed computer code NATFREQ (4). An initial comparison has been made of the NATFREQ-predicted and the measured natural frequencies of the cable with attached masses. Excellent agreement has been obtained and further comparisons are underway.

ACKNOWLEDGEMENTS

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logical Survey, and by a consortium of companies active in offshore engineering: The American Bureau of Shipping, Brown, and Root, Inc., Chevron Oil Field Research, Conoco, Inc., Exxon Production Research, Shell Development Company, and Union Oil Company. The experiments described here were part of a larger program which included tests of a steel pipe at the Castine site. These tests will be described in future publications.

REFERENCES

1. O. M. Griffin, S. E. Ramberg, R. A. Skop, D. J. Meggitt and S. S. Sergev, "The Strumming of Marine Cables: State-of-the-Art," NCEL Technical Note No. N-1608 (May 1981).

2. J. E. Kline, A. Brisbane and E. M. Fitzgerald, "Cable Strumming Suppression," MAR Incorporated Technical Report 249 (July 1980).

3. J. E. Kline, E. Fitzgerald, C. Tyler and T. Brzoska, "The Dynamic Response of a Moored Hydrophone Housing Assembly Subjected to a Steady Uniform Flow," MAR Incorporated Technical Report No. 237 on NCEL Contract No. N68305-78-C-0049 (February 1980).

4. S. S. Sergev and W. D. Iwan, "The Natural Frequencies and Mode Shapes of Cables with Attached Masses," NCEL Technical Note No. N-1583 (August 1980).

5. J. K. Vandiver and T. W. Pham, "Performance Evaluation of Various Strumming Suppression Devices," MIT Ocean Engineering Department Report 77-2 (March 1977).

6. J. K. Vandiver and C. H. Mazel, "A Field Study of Vortex-Excited Excited Vibrations of Marine Cables," Offshore Technology Conference Paper OTC 2491 (May 1976).

7. J. C. McGlothlin, "Drag Coefficients of Long Flexible Cylinders Subject to Vortex Induced Vibrations," M.S. Thesis, MIT Ocean Engineering Department (January 1982).

8. R. A. Skop, O. M. Griffin, and S. E. Ramberg, "Strumming Predictions for the SEACON II Experimental Mooring," Offshore Technology Conference Preprint OTC 2491 (May 1977).

9. O. M. Griffin, "Steady Hydrodynamic Loads Due to Vortex Shedding from the OTEC Cold Water Pipe," NRL Memorandum Report 4698 (January 1982).

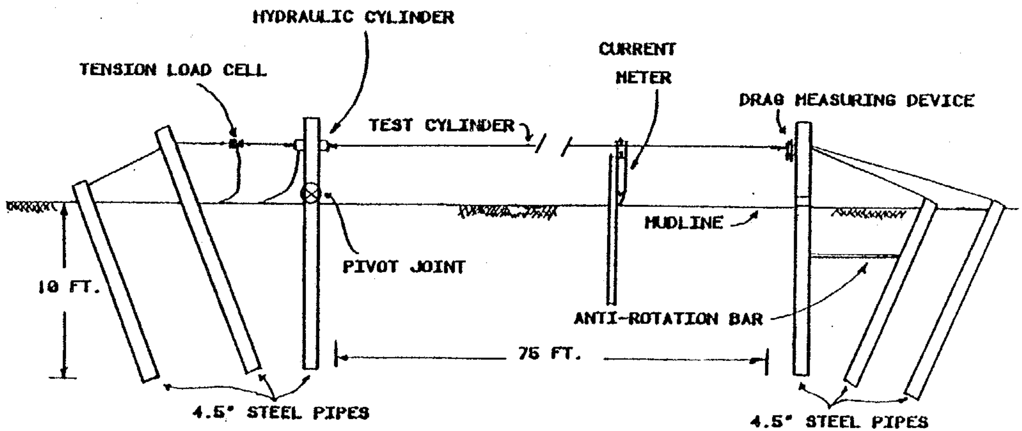

Fig. 1 — Schematic diagram of the field test set-up.

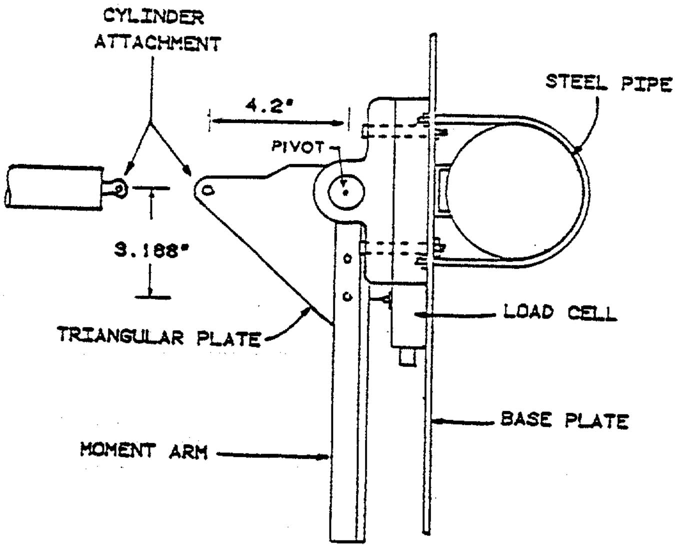

Fig. 2 — Diagram of the drag measuring device — Top View.

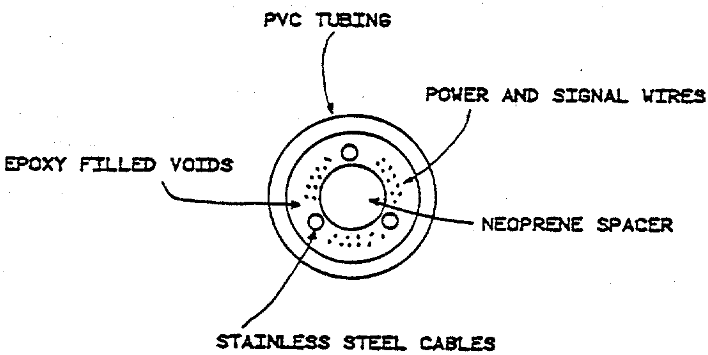

Fig. 3 — Section of the test cable.

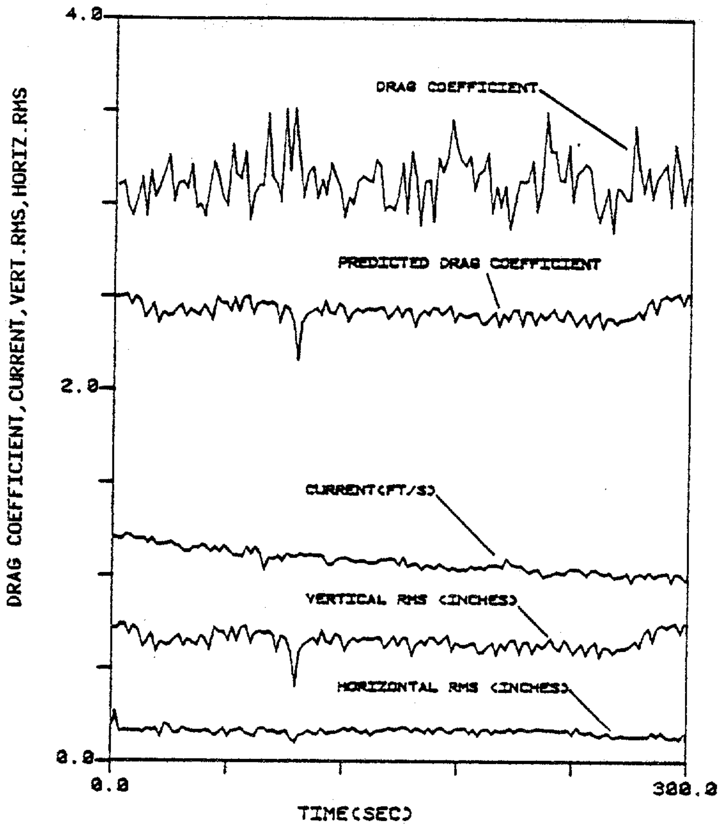

Fig. 4 — Predicted drag coefficient for the bare cable during third mode vertical and fifth mode horizontal responses. Vertical displacement (RMS) at L/6.

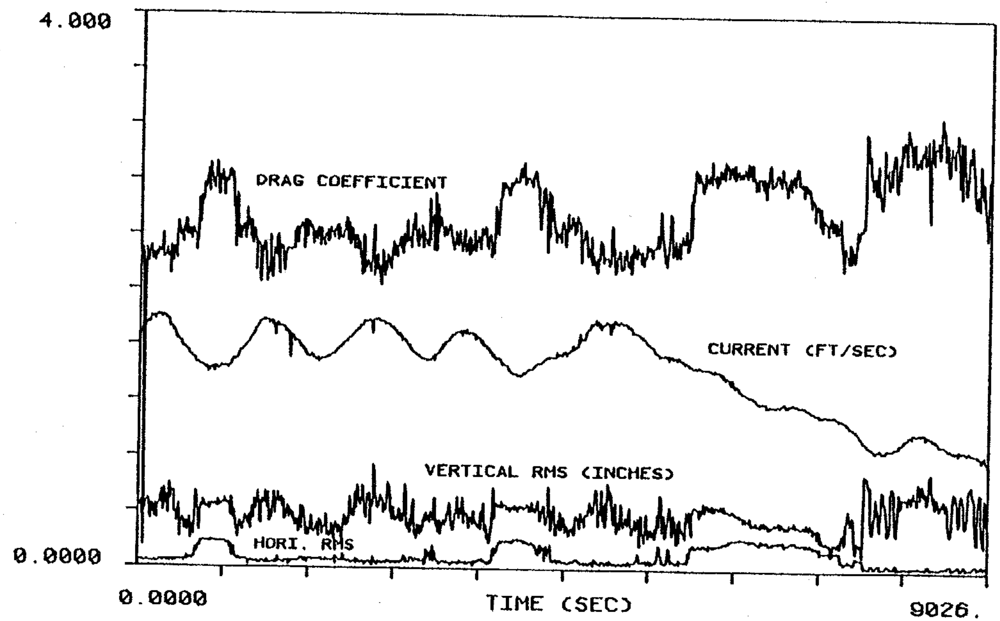

Fig. 5 — Cable with lumped masses 10-Aug-81; RMS displacement data at $x = 3L/4$.

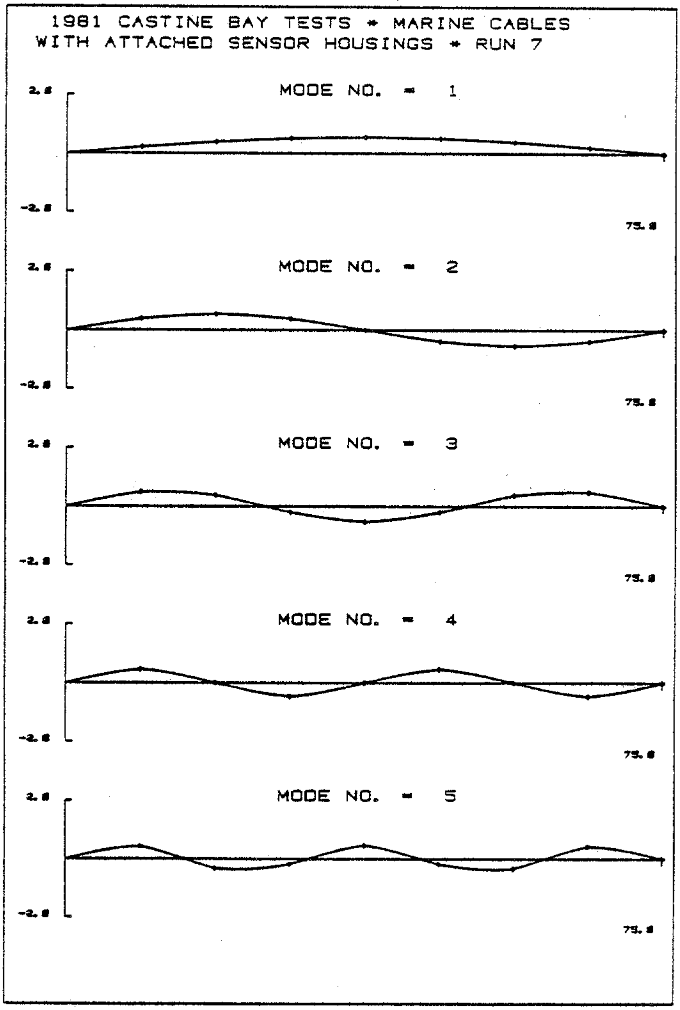

Fig. 6 — Modal vibration patterns computed with NATFREQ. Attached masses at NL/8, N = 1 to 7.